Propagation of DEM Varying Accuracy into Terrain-Based Analysis

W. Katerji, M. Farjas, C.Morillo

Abstract**—**Terrain-Based Analysis results in derived products from an input DEM and these products are needed to perform various analyses. To efficiently use these products in decision-making, their accuracies must be estimated systematically. This paper proposes a procedure to assess the accuracy of these derived products, by calculating the accuracy of the slope dataset and its significance, taking as an input the accuracy of the DEM.

Based on the output of previously published research on modeling the relative accuracy of a DEM, specifically ASTER and SRTM DEMs with Lebanon coverage as the area of study, analysis have showed that ASTER has a low significance in the majority of the area where only 2% of the modeled terrain has 50% or more significance. On the other hand, SRTM showed a better significance, where 37% of the modeled terrain has 50% or more significance.

Statistical analysis deduced that the accuracy of the slope dataset, calculated on a cell-by-cell basis, is highly correlated to the accuracy of the input DEM. However, this correlation becomes lower between the slope accuracy and the slope significance, whereas it becomes much higher between the modeled slope and the slope significance.

Keywords**—**Terrain-Based Analysis, Slope, Accuracy Assessment.

I. Introduction

A Digital Elevation Model (DEM), as an end product, is only useful for visualizing the terrain in perspective view. However the usages of a DEM grow way beyond 3D visualization to perform various analyses, such as terrain morphology, volumetric analysis, visibility and line of sight, and hydrologic analysis.

Previous researches, such as [1], have tackled the accuracy of terrain-based analysis with focus on various algorithms, but with the assumption of a fixed accuracy for the input DEM, and tested using well-defined mathematical models, which does not reflect the true nature of DEMs representing real terrain.

The objective of this paper is to propose a model to propagate the accuracy of a DEM that has been modeled into a vario-model, to assess the accuracy of the products that are the results of performing terrain-based analysis on this DEM, in order to quantitatively and systematically assess the accuracies of these products.

By a mathematical definition, a slope of a line in a two-dimensional Euclidean system describes the steepness of this line, denoted as the ratio of the vertical change over the horizontal change [2]. The slope of a line is also denoted as the angle of that slope, which is calculate using trigonometric functions. Applied to DEM, the slope function in GIS calculates for each cell in the input DEM the slope as the maximum rate of height change between that cell and its 8 surrounding cells, based on 3x3 cell neighborhood [3].

The slope dataset, which is the combination of slope calculation of all the cells that forms the input DEM, is an important indicator to analyze a terrain. The slope dataset is directly used in performing terrain morphology, such as landslide and flood hazard detection, construction sites suitability analysis, and landscaping analysis, as describes in researched such as [4] and [5].

The area of study for this research is Lebanon. Lebanon is situated on the eastern edge of the Mediterranean Sea. as a geographic extent, is very interesting to study because, even though it's a very small country, ranked 170th in the list of countries by area out of 252 countries, it has a rich variation of landscape; It consist of a narrow coast, followed by a rough chain of mountains (Western Chain), followed by a plain valley (the *'Bekaa'* valley), then a less rougher chain of mountains (Eastern Chain) toward the eastern side [6].

II. Materials and Methods

This section describes the proposed procedure for calculating the accuracy and significance of the slope, and the input data used for testing it:

A. Input Data

For the proposed method to be performed, two inputs are required: a DEM, and a vario-model containing its varying accuracy. The input DEM must be as a continuous raster format. The used DEMs in this study are the ASTER GDEM and SRTM:

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) is a freely-available digital surface model (DSM) with a spatial resolution of 30 meters and an assumed accuracy varying between 10 and 25 meters. The GDEM product, which is based on stereoscopic imagery, has

W. Katerji is a PhD candidate at E.T.S.I. en Topografía, Geodesia y Cartografía, Universidad Politecnica de Madrid, Avenida del Mediterráneo km 7,0 (Calle Mercator 2), 28031 Madrid, Spain (phone: 961-3-762623; e-mail: w.katerji@alumnos.upm.es).

M. Farjas is a professor at E.T.S.I. en Topografía, Geodesia y Cartografía, Universidad Politecnica de Madrid, Avenida del Mediterráneo km 7,0 (Calle Mercator 2), 28031 Madrid, Spain.

M. Morillo is a professor at E.T.S.I. en Topografía, Geodesia y Cartografía, Universidad Politecnica de Madrid, Avenida del Mediterráneo km 7,0 (Calle Mercator 2), 28031 Madrid, Spain.

orthometric heights that are based on the EGM96 geoid.[7]

Shuttle Radar Topography Mission (SRTM) is another freely-available DSM with a spatial resolution of 90 meters and height accuracy of 20 meters. While height measurements based on orbiting satellite are geodetic, the dataset are processed and available to the public with orthometric heights that are based on the EGM96 geoid. [8]

The input vario-model must be formatted and stored as a continuous raster format, with the same extent and spatial resolution (cell-size) as its related input DEM. The vario-model must store the relative height accuracy for each coincident cell in the related DEM, and expressed in the same linear unit as the DEM. The design and implementation of the vario-model is beyond the scope of this paper, and the proposed model assumes that this input is based on a robust and representative methodology. Specifically, this paper will rely on an existing model that is based on land-use/land-cover classification of the terrain, and that is already been published in [9].

While the proposed methodology can be applied to any datasets from around the world, provided the requirements as described above, it will be demonstrated in this paper using the same coverage as in [9], which is the extent of Lebanon.

B. Accuracy of Slope

A DEM is a modeled representation of the terrain. Similar to any taken measurement in any field of science and engineering, and irrespective to the technique of data collection and modeling, the height values stored inside the DEM contain some error with respect to the reality. The error will be referred to the accuracy of the measurement. Therefore, for each cell, the modeled height value can be denoted as follow:

$$Z_{model} = Z_{actual} \pm \varepsilon_z \qquad (1)$$

where ε_z is the individual or absolute accuracy of each cell of the DEM, and:

$$\Delta Z_{modele} = \Delta Z_{actual} \pm \varepsilon_{\Delta z} \qquad (2)$$

where $\varepsilon_{\Delta z}$ is the relative accuracy for each cell of the DEM with respect to its neighbor.

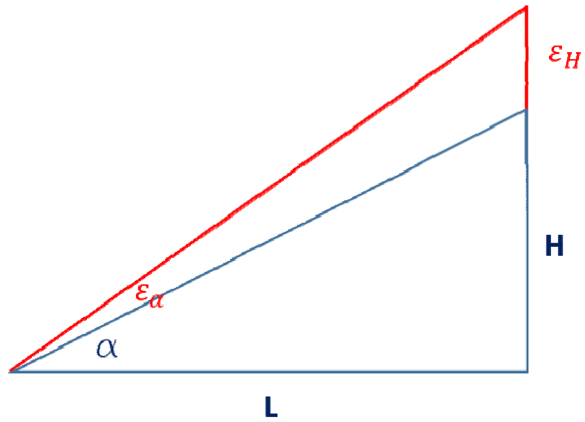

Fig. 1 Mathematical representation of the slope and its accuracy

Therefore the accuracy of the slope is calculated as follows when applied to the whole terrain on a cell-by-cell basis

$$\varepsilon_\alpha = \left| \tan^{-1}\left(\tan Slope(DEM) + \frac{\varepsilon_{\Delta z}}{Cell\ Size}\right) - Slope(DEM) \right| \qquad (3)$$

where: Slope(DEM) is the slope dataset derived from the input DEM, expressed in angular unit; $\varepsilon_{\Delta z}$ is the relative accuracy of the DEM (constant value or vario-model), expressed in linear unit; Cell Size is the cell size of the DEM, expressed in same linear unit as $\varepsilon_{\Delta z}$; and ε_α is the accuracy of the slope dataset, expressed in the same angular unit as the slope.

C. Significance of Slope

The significance of the slope or of any derived value is the level of accuracy to which this modeled value represents the actual one. The significance represents the percentage of how much the modeled value is close to the actual one, and is calculated as follows:

$$Sig(\alpha_{model}) = 1 - \frac{\varepsilon_\alpha}{\alpha_{model}} \quad \text{If:} \quad \varepsilon_\alpha \leq \alpha_{model} \qquad (4)$$

Or

$$Sig(\alpha_{model}) = 0 \quad \text{If:} \quad \varepsilon_\alpha > \alpha_{model} \qquad (5)$$

III. Analysis of Results

This section describe visually and statistically the results of the proposed methodology applied to the input datasets described in section II.*A*

A. Results Description

The input DEM relative accuracy models for both DEMs had the following ranges of values: ASTER (Range between 8.7 and 19.2 meters, with an average accuracy of 14.2 meters) and SRTM (Range between 1.5 and 14.5 meters, with an average accuracy of 9.5 meters). Based on these input, it is important to note that SRTM has a higher relative accuracy compared to ASTER, even though the former has a lower spatial resolution compared to the latter.

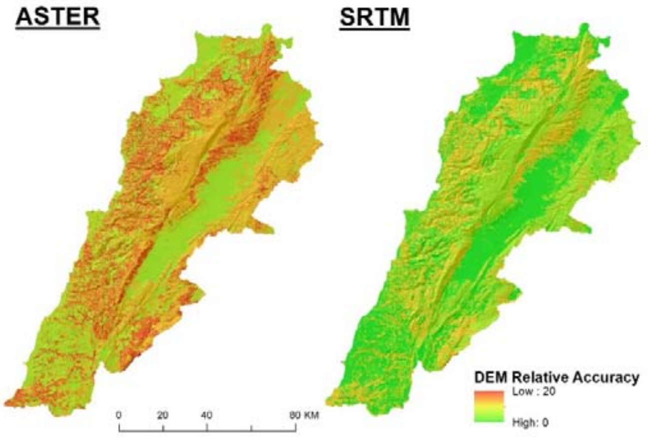

Fig. 2 Maps of Lebanon showing the input DEM relative accuracy models for ASTER and SRTM DEMs

After applying the proposed procedure in section II.*B*, the slope accuracy for both DEMs gave the following results: ASTER has the slope accuracy ranging between 0.9 and 32.5 degrees, with an average accuracy of 21.9 degrees. SRTM has the slope accuracy ranging between 0.7 and 9.1 degrees, with an average accuracy of 5.5 degrees. The results show a noticeable difference between the two DEMs, where SRTM has much higher slope accuracy than ASTER. This high difference is mainly due to the propagation of the input DEM accuracy, and adding to it the cell size which has an inverse weight on the result.

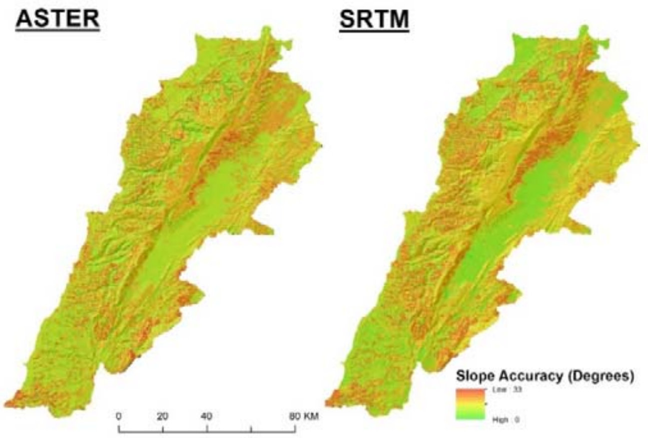

Fig. 3 Maps of Lebanon showing the generatedslope accuracy models for ASTER and SRTM DEMs

Finally, after applying the proposed procedure in section II.*C*, the significance of the slope for both DEMs gave the following results: Both DEMs have a range between 0 and 98 %; however the average slope significance for ASTER is 5.2%, compared to 35.3% for SRTM.

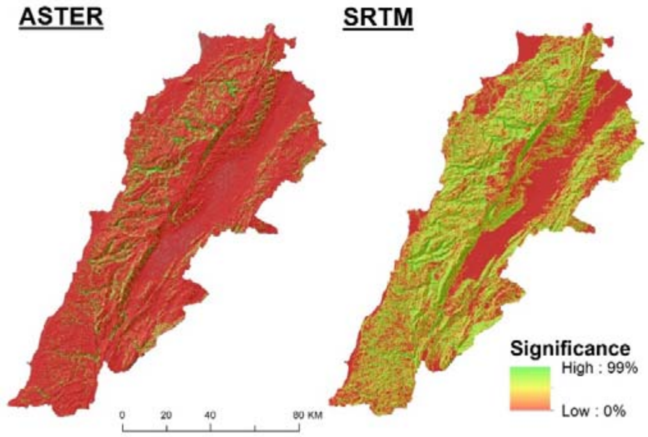

Fig. 4 Maps of Lebanon showing the generatedslopesignificance models for ASTER and SRTM DEMs

Visual inspection of the above map clearly shows that using SRTM will lead to significant results for any derived terrain-based analysis in the majority of the country, in the exception of few coastal regions on the western border and in the middle of the Bekaa valley in the center. On the other hand, using ASTER will only lead to significant results in steep-slopes valley edges.

B. Correlation Analysis

In this research, several datasets were involved in the process, as input, intermediate, or output data. These datasets are: DEM, DEM accuracy model, Slope, Slope Accuracy Model, and Slope Significance Model. Using an advanced statistical package (SPSS), the Pearson correlation is created for each dataset pair in both products, along with the significance (p-value) of each.

TABLE I
PEARSON CORRELATION MATRIX FOR ASTER

ASTER	DEM	DEM Accuracy	Slope	Slope Accuracy	Slope Significance
DEM	1	-	-	-	-
DEM Accuracy	0.254	1	-	-	-
Slope	.149	0.404	1	-	-
Slope Accuracy	0.176	0.686	-0.323	1	-
Slope Significance	0.049	0.152	0.767	-0.486	1

TABLE II
PEARSON CORRELATION MATRIX FOR SRTM

ASTER	DEM	DEM Accuracy	Slope	Slope Accuracy	Slope Significance
DEM	1	-	-	-	-
DEM Accuracy	0.226	1	-	-	-
Slope	0.177	0.445	1	-	-
Slope Accuracy	0.215	0.955	0.196	1	-
Slope Significance	0.106	0.100	0.848	-0.107	1

As a first observation, the correlations behaved similarly for both products ASTER and SRTM, even though the individual values of these datasets were not consistent at all between these two products. Accordingly, any deduction from these matrices concerning the correlation between any two datasets will be considered product-independent. Some interesting deductions:

The DEM has a low correlation with all the other datasets. This is due to the fact that the calculation of the slope is based on the relative difference of heights between a cell and its neighbors, irrespective of the cell absolute height, which is generally in reference with the mean sea level.

In the opposite of the first point, the DEM accuracy is highly correlated to the Slope accuracy. In fact there should be high correlation between the two datasets, as the second one is dependent to the first, as in the procedure described in section II.*B*.

The most interesting observation is that there is a low correlation between the slope accuracy and the slope significance, while the proposed equation in section II.*C* misleads that there should be a high correlation as the slope significance is dependent on the slope accuracy. However the slope significance has a relatively positive high correlation with the actual slope.

IV. Conclusion

In this research, a procedure is proposed to propagate the height accuracy of an input DEM in order to estimate the accuracy of its terrain-based analysis derived datasets. To test the proposed procedure, two global DEMs were used, the ASTER and SRTM, covering Lebanon as the area of study, and vario-models containing the varying relative accuracies of each, to calculate the accuracy and significance of their derived slope datasets. Slope significance being modeled as percentage to which the slope, and any other derived dataset, is estimated to provide a compliant result with respect to the actual reality.

Test performed on these two DEMs showed that even though ASTER has a higher spatial resolution than SRTM, the derived datasets from the latter will have higher significance. Several elements played part in this comparison, mainly the DEMs vario-models, where ASTER was modeled having lower relative accuracy than SRTM.

Multivariate spatial analysis highlighted further deduction mainly that the correlation between the different datasets was proven to be product-independent, and therefore could be considered applicable to other DEM products. Also, this analysis showed that the slope accuracy is highly related to the DEM accuracy, but the ultimate product that is of interest in this paper, which is the slope significance is more related to the actual slope rather that its accuracy.

This will lead to the ultimate conclusion that analysis performed on relatively low accuracy DEMs applied in steep sloped areas will still lead to significant results, while the flatter areas would require a more accurate DEM to reach the same level of significance.

Applied to Lebanon, the ASTER DEM gives significant results only in the steep slopes valley, whereas the SRTM DEM can be applicable both the Western and Eastern chains. The coast and the Bekaa valley, due to their flat nature, would require a more accurate DEM in order to retrieve significant results.

References

[1] Zhou, Q., & Liu, X. (2004), *“Analysis of errors in derived slope and aspect related to DEM data properties”*, Elsevier Computers & Geosciences 30, 369-378.

[2] Clapham, C., & Nicholson, J. (2009), *“Oxford Concise Dictionary of Mathematics”*, Addison-Wesley.

[3] Burrough, P., &McDonell, R. (1998), *“In Principles of Geographic Information Systems”*, (p. 190). New York: Oxford University Press.

[4] Wu, S., Li, J., & Huang, G. (2008), *“Characterization and Evaluation of Elevation Data Uncertainity in Water Resources Modeling with GIS”*, Springer Water Resource Management, 959-972.

[5] Mutluoglu, Ö. (2010), *“Investigation of the effect of land slope on the accuracy of digital elevation model (DEM) generated from various sources”*, Academic Journal - Scientific Research and Essays Vol. 5(11), 1384-1391.

[6] *“Lebanon Geography”*, (2014). Retrieved September 9, 2014, from CIA World Fact Book: https://www.cia.gov/library/publications/the-world-factbook/geos/le.html

[7] Tan, H. (2004, September 7), *“ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer”*, Retrieved from NASA Jet Propulsion Laboratory: http://asterweb.jpl.nasa.gov/

[8] Ramirez, E. (2009, June 17), *“Shuttle Radar Topography Mission”*, Retrieved from NASA Jet Propulsion Laboratory: http://www2.jpl.nasa.gov/srtm/

[9] Katerji, W., &Farjas, M. (2014), *“DEM Accuracy Patterns in Land-Use/Land-Cover Classification - Case Study of Lebanon”*, 5th GEOBIA. Thessaloniki: South-Eastern European Journal of Earth Observation and Geomatics.